Public Health Burden of E-waste in Africa

Orish Ebere Orisakwe[1], **Chiara Frazzoli**[2], **Cajetan Elochukwu Ilo**,[3] **Benjamin Oritsemuelebi**[1]

1 Department of Experimental Pharmacology & Toxicology, Faculty of Pharmacy, University of Port Harcourt, Port Harcourt, Nigeria
2 Department for Cardiovascular, Dysmetabolic and Aging-Associated Diseases, Istituto Superiore di Sanità, Rome, Italy
3 Department of Pharmacology, College of Health Sciences, Nnamdi Azikiwe University, Nnewi Campus, Nnewi, Nigeria

Corresponding author:
Orish Ebere Orisakwe
orishebere@gmail.com

Background. Environmental impacts from informal e-waste recycling are increasing in Africa. E-waste handling and disposal exposes people to highly toxic cocktails of heavy metals, brominated flame retardants, non-dioxin-like polychlorinated biphenyls (PCB), polycyclic aromatic hydrocarbons (PAH), polychlorinated dibenzo-p-dioxins (PCDD), polychlorinated dibenzofurans (PBDF) and dioxin-like polychlorinated biphenyls (DL-PCB). Most of these compounds are endocrine disrupters, and most are neuro- and immune-toxic as well.
Objectives. Informal e-waste recycling in African countries is a serious public health threat. The present paper reviews the extent of e-waste exposure in Africa and related impacts on people, animals and the environment.
Methods. Four electronic databases (PubMed, Science Direct, Scopus, Google Scholar) were searched for publications related to e-waste and human health in Africa. Search terms included 'e-waste in Africa', 'e-waste in developing nations', 'public health and e-waste', 'environment and e-waste', and 'e-waste and health'.
Discussion. Elevated levels of e-waste pollutants in water, air, soil, dust, fish, vegetable, and human matrices (blood, urine, breast milk) indicate that not only are e-waste workers at risk from exposure to e-waste, but the general population and future generations as well. Headache, cough and chest pain, stomach discomfort, miscarriage, abnormal thyroid and reproductive function, reduction of gonadal hormone, and cancer are common complaints of those involved with the processing of e-waste.
Conclusions. The evidence presented from the reviewed studies illustrates the extent of the human health and environmental risks posed by e-waste in Africa. There is a need for a regulatory framework including specific legislation, infrastructure and protocols to safely recycle and dispose of e-waste in sub-Saharan African countries.
Competing Interests. The authors declare no competing financial interests.
Keywords. E-waste, environmental health, exposure, risk assessment, Africa
Received January 15, 2019. Accepted May 8, 2019.
J Health Pollution 22: (190610) 2019

Introduction

Modernization and civilization have led to a growth in technology. Electronic gadgets have been developed to aid information and communication ranging from radios, computers and peripheral items, telephones, televisions, and other household consumer electronics and vehicles. The production, commercialization, use, recycle, and disposal of electrical and electronic equipment (EEEs) have increased exponentially in the last decades. The rapid increase of new technologies makes EEEs obsolete, sometimes within days of purchase. Large quantities of e-waste end up dumped in low income countries, where second-hand materials come mixed with broken parts. Most of the electronic gadgets used in Africa have second hand value and reach their half-life soon after they are imported and go obsolete, contributing to the rapid increase of e-waste in Africa. Once it is beyond repair, e-waste is dumped and presents a hazard to the environment, animals and humans.[1] A large range of toxic chemicals (toxicants) are associated with this e-waste.[2] Inorganic and organic toxicants can be released from e-waste, posing serious risks of harm to human health and the environment.[3,4] Electrical and electronic equipment are mostly made from petrochemicals, glass, electrical and electronic components which are not biodegradable, including:

i) chemical elements such as aluminium (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), hexavalent chromium (CrVI), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), lithium (Li), manganese (Mn), mercury (Hg), nickel (Ni), tin (Sn), zinc (Zn) and groups like the platinum group elements and rare earth elements.

ii) brominated flame retardants (BFRs). These have historically been added to materials, especially plastics (thermoplastic components, cable insulation) in computers to improve their fire resistance. The main examples are polybrominated biphenyls (PBBs), tetrabromobisphenol-A (TBBP-A), and poly-brominated diphenyl ethers (PBDEs). Brominated flame retardants are persistent organic pollutants (POPs).

iii) non-dioxin-like polychlorinated biphenyls. The major use of non-dioxin-like polychlorinated biphenyls has been as dielectric fluid in electrical equipment, particularly capacitors and transformers, in heat transfer fluids and as plasticizers and additives in lubricating and adhesives and plastics. Non-dioxin-like polychlorinated biphenyls are also POPs.

Other e-waste-related toxicants arise from common e-waste practices like e-waste combustion, such as various congeners of polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins (PCDDs), polybrominated dibenzo-p-dioxins (PBDDs), polychlorinated dibenzofurans (PCDFs), polybrominated dibenzofurans (PBDFs), and dioxin-like polychlorinated biphenyls (DL-PCBs).[5]

The volume of EEEs that have accumulated as waste worldwide is also of great concern. High-volume informal recycling of e-waste has been reported in many countries, including China, Ghana, India, Nigeria, the Philippines, Thailand, and Vietnam. E-waste management is one of the most rapidly growing pollution problems worldwide.[2,5] African exposure scenarios have been difficult to assess until recently due to limited information on e-waste-related exposures in major e-waste sites such as West Africa. The situation is changing, and the African scientific community has begun to collect analytical evidence on e-waste contamination of environmental media and human internal exposure, as well as associated health outcomes.

Based on the above, this work summarizes current e-waste contamination and recycling practices in Africa, the measured hazards associated with such activities, and reported/diagnosed health effects in resource-poor and technologically challenged countries in sub-Saharan Africa. This review will not only add to the foundation of knowledge, but can also support public health initiatives in sub-Saharan Africa.

Abbreviations			
BFRs	Brominated flame retardants	*PBBs*	Polybrominated biphenyls
BLLs	Blood lead levels	*PBDDs*	Polybrominated dibenzo-p-dioxins
CRT	Cathode ray tube	*PBDEs*	Poly-brominated diphenyl ethers
DecaBDE	Decabromodiphenyl ether	*PBDFs*	Polybrominated dibenzofurans
DL-PCBs	Dioxin-like polychlorinated biphenyls	*PCBs*	Polychlorinated biphenyl
DRCs	Dioxin-related compounds	*PCDDs*	Polychlorinated dibenzo-p-dioxins
dw	Dry weight	*PCDD/Fs*	PPolychlorinated dibenzo-p-dioxins/furans
EEFs	Electrical and electronic equipment	*PCDFs*	Polychlorinated dibenzofurans
lw	Lipid weight	*TBBP-A*	Tetrabromobisphenol-A
PAHs	Polycyclic aromatic hydrocarbons		

Methods

Four electronic databases (PubMed, Science Direct, Scopus, Google Scholar) were searched for publications related to e-waste and human health in Africa. Search terms included 'e-waste in Africa', 'e-waste in developing nations', 'public health and e-waste', 'environment and e-waste', and 'e-waste and health'. Duplicates from papers (64 in PubMed, 1306 in Science Direct, 1306 in Scopus, 3750 in Google Scholar) were removed, and 364 articles remained. Among these, only those published in the English language from 2011 to 2018, and those relating to the African continent were included. After selection according to the above method of identification and criteria for selection of studies (*Figure 1*), papers were screened for both analytical levels of inorganic and

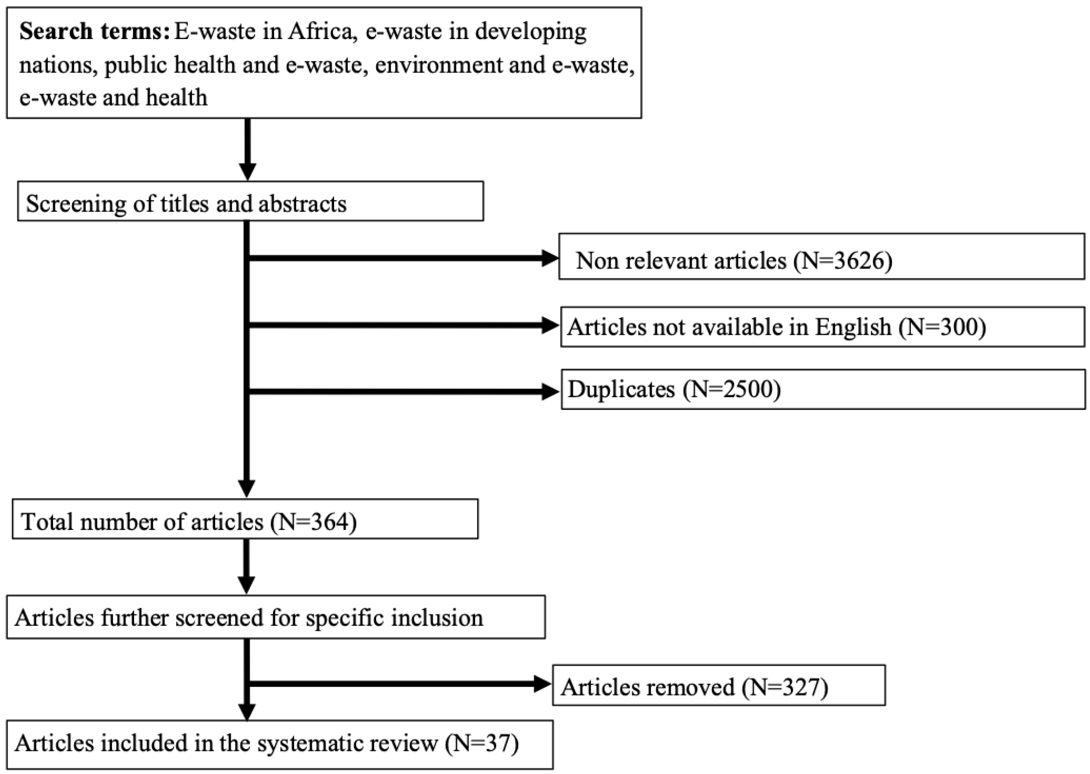

Figure 1 — PRISMA flow diagram indicating the number of articles that were identified, screened and included in this review

organic e-waste toxicants associated with specific components of EEEs found in environmental and human matrices in Africa, and e-waste associated human health effects in Africa.

Results

Applying the screening methods describes above, 37 papers were screened in the present review. Of these, 25 papers reported analytical levels of e-waste-related toxicants environmental matrices in Africa, and 12 reported on human matrices in Africa (*Table 1*).

Nigeria (Alaba international electronic market and Ikeja computer village in Lagos) and Ghana (Agbogbloshie, Accra) have been reported to be major e-waste dumpsites in Africa.[6,7] The Supplemental Material presents published African analytical data (notably from Ghana, Nigeria, Kenya, Morocco and South Africa) on primary e-waste related toxicants and reported/diagnosed health effects in exposed (sub)populations. In particular, the first table in the Supplemental Material focuses on inorganic and organic toxicants found in environmental (including food) matrices, whereas the second table focuses on inorganic and organic toxicants in human matrices.

Discussion

In their study on plastic resin pellets collected from 11 beaches covering the entire Ghanaian coastline, Hosoda and co-workers analyzed polychlorinated biphenyl (PCBs) and found that PCB concentrations (∑13 congeners) were higher in Accra, the capital city, and Tema (39-69 ng/g-pellets) than those in rural coastal towns (1–15 ng/g-pellets), which are close to global background levels.[8] All PCBs concentrations in plastic pellets manufactured near Accra were reported to be higher than global background levels, indicating local inputs of PCBs.[8] In the same study, river sediments were also analyzed for PCBs together with molecular markers,

	Number of papers	Countries	E-waste-related inorganic toxicants	E-waste-related organic toxicants	Reported health effects
Environmental matrices	25	West African coast, Ivory Coast, Gambia, Ghana, Kenya, Nigeria, South Africa	Fe, Al, Zn, Cu, Pb, Co, Cd, Cr, Mn, Ba, Sn, V, As, Sb, Br, Cl, Hg,	PCB, PBDD, PBDF, DL-PCB, PCDD, PAHS PBDE, Octa-BDE TBBP-A, PBB	-Abnormal thyroid and reproductive function, Reduction of gonadal hormone, Injuries and respiratory symptoms, Cough and chest pain, Headache, stomach discomfort, miscarriage, and cancer
Human matrices	12	Ghana, Nigeria, Guinea – Bissau, Morocco	As, Cd, Cr, Hg, Fe, Ag, Al, Be, Cd, Co, Hg, Mn, Pb, Sb, V, Ga, Mn, Mo, Sr, Zn, Cs, Bi, Ba, Ag,	PCB, PBDE, HBCDS, PCDD, PAH	-Reduction of gonadal hormone - Depletion of antioxidant reserves - Injuries and respiratory symptoms - Cough and chest pain

Abbreviations: Br, bromine; Cl, chlorine; Ag, silver; V, vanadium; Ga, gallium; Mo, molybdenum; Sr, strontium; Cs, caesium; Bi, bismuth; PCB, polychlorinated biphenyl; Octa-BDE TBBP-A, Octa-brominated diphenyl ethers Tetrabromobisphenol A; HBCDs, hexabromocyclododecane.

Table 1 — Studies Reporting Analytical Levels of Inorganic and Organic E-Waste-Related Toxicants in African Environmental and Human Matrices and Associated Health Effects

and sedimentary PCB concentrations were highest at a site downstream of an e-waste scrapyard.[8] In Ghana, PCBs are introduced to the river in greater proportion from e-waste site than from activities in downtown Accra, with relatively higher PAH concentrations in urban areas with a strong petrogenic fingerprint.[8] The high levels of triphenylbenzenes found in Ghana suggest plastic combustion near e-waste scrapyards.[8]

In addition to PCBs, highly persistent BFRs are of public health concern with respect to their endocrine disrupting action.[9] The indiscriminate dumping of cathode ray tube (CRT) casings has added to the plastic explosion in Nigeria. In Nigeria and other African countries, farm land, backyards and waste dumps are inundated with CRT casings. Assessing the presence of PBDEs and how they are handled is therefore crucial. In a study to assess the presence of PBDE and other BFRs aimed at developing an inventory for PBDEs in the plastic components of CRTs from television sets and computer monitors in Nigeria, the authors reported that average PBDE levels (of commercial octabromodiphenyl ether + decabromodiphenyl ether (DecaBDE)) in Nigerian-stockpiled CRT casings were 1.1% for TVs and 0.13% for personal computer CRTs.[10] These values exceed the restriction of hazardous substances limit and therefore require separation from the restriction of hazardous substances compliant recycling.[10] The Nigerian e-waste inventory of 237,000 tons of CRT plastic contain approximately 594 tons commercial octabromodiphenyl ether and 1880 tons of DecaBDE.[10]

Sub-Saharan African countries without state-of-the-art recycling plants and with little or no monitoring or measurement capacity for the hazardous contaminants in e-waste are confronted with the challenge of controlling PBDE in plastics and sundry articles/products and in recycling flows. Since Nigeria and other sub-Saharan African countries lack appropriate destruction facilities, open burning or dumping of hazardous wastes and subsequently widespread environmental pollution become inevitable.[11,12] During periods of heavy rainfall, much of the site becomes flooded and run-off waters irrigate farm lands. Samples of sediments collected from a shallow lagoon located near the disposal and open burning areas within the Agbogbloshie market, Ghana contained very higher metal concentrations and organic chemicals.[13] In Agbogbloshie, Oteng-Ababio *et al.* found different congeners of PBDEs in both soils and vegetables.[14] Soil and ashes samples taken at burning sites in Agbogbloshie showed extremely high concentrations of Cd, Cu, Pb, Sb, and Sn as compared to those typically seen in uncontaminated soil.[13]

As reported in the Supplemental Material, when released into the environment, chemical elements contaminate the air, surface and groundwater, sediment, biota and soil.[15]

Copper and Pb are the most predominant contaminants among chemical elements in both soil and vegetable samples from e-waste dumpsites.[16] The Cu level (4308 mg/kg) exceeded the new Dutch list action value of 190 mg/kg and the soil Pb level (1535 mg/kg) exceeded the Dutch action value of 530 mg/kg.[16] Air samples from the Agbogbloshie market located in Accra, Ghana have been analyzed to assess levels of metals and corresponding exposure of workers and people within the vicinity of the market. The site is known to be a dismantling and trading area for end of life electronic items, as well as an informal processing and dumping site. Both air and soil in these and surrounding regions were found to be heavily polluted. Air samples from Agbogbloshie market had high levels of Al, Cu, Fe, Pb, and Zn.[17] Over half of the soil samples collected from Agbogbloshie market were above the United States Environmental Protection Agency standard for Pb in soil (400 mg/kg or ppm).[18] The lowest Pb level in the soil was 134 ppm and the highest is 18,125 ppm.[17] Heavy metal analysis of e-waste samples from Alaba international electronic market and Ikeja computer village in Nigeria showed the presence of Cd, Cr, Ni, Mn, Cu, and Pb at different concentrations, some of which were higher than the limits set by international regulatory authorities.[16]

Igbo and co-workers investigated the impact of e-waste leachate on micronuclei formation in *Tilapia guineensis* and levels of heavy metals (As, Al, Ba Cd, Cr, Hg, and Pb) in sediments, water, leachate and aquatic fauna (*Tilapia guineensis, Callinectes amnicola* and *Cardisoma armatum*).

An investigation of the interplay of metals (Co, Cu, Fe, Pb, strontium (Sr), and Zn) and bromine (Br) in the formation of dioxin-related compounds (DRCs), including polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs) and DL-PCBs, as well as non-regulated DRCs such as polybrominated dibenzo-p-dioxins/furans and their monobrominated PCDD/Fs in soils sampled from open burning e-waste sites at Agbogbloshie revealed that the predominant DRCs were PBDFs, PCDFs, PCDDs, and DL-PCBs.[19] Bromine contained in various e-wastes, wires/cables, plastics, and tires strongly influenced generation of many DRCs.[19] Soil samples from the e-waste sites at Agbogbloshie are severely polluted by toxic metals and DRCs (PCDD/Fs, polybrominated dibenzo-p-dioxins/furans, and monobrominated PCDD/Fs).[19] The summary of PBDFs and PCDD/Fs constituted 94% of the total toxicity equivalent value concentrations of DRCs.[19] The PCDF/PCDD ratio indicated a selective formation of PCDFs over PCDDs. The predominant formation of PBDFs rather than PBDDs was also found. Excess formation of monobrominated PCDFs (i.e., high monobrominated PCDF/monobrominated PCDD ratio) may be a common trend pertaining to the burning of e-waste containing BFRs.[19]

In what is perhaps the first study from the African region on the presence of PBDEs and PCBs in the indoor dust of e-waste recycling facilities, PBDEs were detected in all samples in concentrations higher than levels reported in Guiyu, China in indoor dust from e-waste workshops, and also higher than levels reported by Tue *et al*.[20,21] The following PCBs were also detected in the same South African study: PCB 28, PCB 153 and PCB 180. The most predominant PCBs 153 and 180 have been detected in wild bird eggs in South Africa.[22]

The PCB levels in sediments from Accra (0.57-32.2 ng/g dry weight (dw)) are lower than in some developed countries and large e-waste sites in China, but higher or comparable with levels in Japan or developing countries (Vietnam, Indonesia, Senegal, India, Philippines).[8] The highest PCB level in Accra (32.2 ng/g dw) exceeded the effects range-low level of sediment quality guideline (22.7 ng/g)[23] of the US National Oceanic and Atmospheric Administration (NOAA). This observation suggests that the likely biological effect of PCBs cannot be ignored near e-waste sites in developing countries.

Human exposure

Humans come into contact with e-waste toxicants in air (e.g. open burning), soil (e.g. disposal), water via ingestion (e.g. food chains contamination due to disposal and primitive recycling processes), inhalation, and dermal absorption (e.g. dust and direct exposure of workers who labor in primitive recycling areas and their families).[3,5] As reported in the Supplemental Material, sources of exposure range from water (including watering sources), aquatic life and farm land. E-waste related toxicants are generally persistent (i.e. resistant to biodegradation) with strong tendency to bioaccumulate in agricultural lands and be available for uptake by grazing livestock and long-range transport.[5]

Drinking and cooking water from the Alaba international electronic markets and Ikeja computer village have been shown to contain heavy metals and POPs.[24,25]

Burning poses the highest risk as those who burn e-waste tend to have the highest and elevated blood lead levels (BLL). In Ghana, higher BLL ranges were found among e-waste workers (0.50-18.80 μg/dL) than non-e-waste workers (0.30-8.20 μg/dL).[26] Asante *et al.* found that concentrations of Pb in urine of e-waste recycling workers in Agbogbloshie were significantly higher than those of reference sites.[49] In another study by Akortia *et al.* evaluating concentrations of trace metals in Agbogbloshie, the authors concluded that the surface soils increased in metal concentrations from moderate to high respect to pre-industrial estimated background values, particularly for Cu, Fe and Pb.[27] Srigboh *et al.* characterized exposures to heavy metals and toxic elements (As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, selenium, Zn) in the blood and urine of male e-waste workers and female service workers at Agbogbloshie, and concluded that e-waste workers have elevated Cd and Pb levels in their blood, and elevated As levels in their urine.[28] Among exposed workers at Agbogbloshie market, levels of Al, Cu, Fe, and Pb were above the American Conference of Governmental Industrial Hygienists threshold limit (ACGIH TLV). For Al, the ACGIH TLV is 1.0 mg/m^3 and the highest reading was 6.5 mg/m^3. One of the volunteers had an airborne exposure level of 0.98 mg/m^3 or 20 times the allowable ACGIH TLV level of 0.05 mg/m^3. Another volunteer had Al exposure levels of 17 mg/m^3, seventeen times the ACGIH TLV guideline of 1.0 mg/m^3.[17] Levels of As, Cd, Cr, and Hg in blood of e-waste workers in Benin, Nigeria have been reported to reduce gonadal hormones.[29] Occupational air exposure to Cd and Pb has been linked to chest and respiratory tract associated symptoms, headaches and stomach discomfort in Ghana.[30] Skin problems, nausea, allergies, aches and migraine were also reported by e-waste workers and residents within the Alaba international electronic markets and Ikeja computer village in Lagos, Nigeria, probably as a result of exposure to e-waste.[31] The investigation of metal urinary levels among primitive recycling of e-waste workers in Ghana (which found elevated Fe, Sb, and Pb concentrations) indicate exposure through the e-waste recycling process. Similarly, high concentrations of these metals have been detected in soil/ash mixtures from the e-waste recycling area in Ghana.[32]

The most predominant PCBs 153 and 180 have been detected in human breast milk in South Africa.[33] Asante *et al.* analyzed PCBs, PBDEs and hexabromocyclododecane in human breast milk samples in Ghana.[34] Although the PBDE (0.86-18 ng/g lipid weight (lw)) and PCB (15-160 ng/g lw) levels were lower than values in Chinese e-waste processing sites, breast milk levels found in Ghana (a much less industrialized country) are considered of public health importance. Following the detection of somewhat high levels of PBDEs in breast milk samples in three main regions in Ghana, the authors argued that in addition to neurodevelopmental deficits and cancer, a toxicological endpoint of concern for environmental levels of PBDEs is likely also thyroid hormone disruption.[34] The source of these pollutants is believed to be the informal handling and disposal of e-waste.[34] Polycyclic aromatic hydrocarbons metabolites were analyzed in the urine of residents and workers from an e-waste processing site in Agbogbloshie and were found to be significantly higher than a control group. Two thirds of the workers reported experiencing cough symptoms, while one quarter reported having chest pain.[35]

Current e-waste handling practices

In Ghana, Nigeria and Morocco, recycling of e-waste often takes place directly on unfortified ground which releases harmful substances directly into the soil. Insulating foam from dismantled refrigerators (primarily polyurethane), CRTs, plastic pellets and old car tires are the main fuels used for fires, contributing to acute chemical hazards and longer term contamination at burning sites.[13] Incomplete combustion of chlorinated organic materials, including polyvinyl chloride coated wires, with the reaction catalyzed by metals such as Cu releases dioxins and furans (PCDDs/Fs) to areas surrounding burning sites leading to contamination of surface soils and air.[13] Due to very poor infrastructure and inadequate implements, recyclers in sub-Saharan Africa resort to the use of primitive methods (e.g. mechanical shredding and open burning) to remove plastic insulation from copper cables. This technique may release highly toxic chemicals and poses a threat to the environment and human health. The primitive and hazardous techniques used for recycling e-waste lead to elevated levels of e-waste-related (mixtures of) toxicants in the environment, including the food chain, and high body burden in residents and workers at e-waste sites. Very high concentrations of organic toxicants (such as PCBs, PBDEs and PBBs) in air, ash, dust, soil, water and sediments in e-waste recycling sites is partly due to uncontrolled combustion and thermal processing of e-waste.[8,12,36] During periods of heavy rainfall, much of the e-waste site becomes flooded and run-off waters irrigate farm lands. E-waste-related toxicants can enter living organisms, from food producing animals to humans through the gastrointestinal tract, as well as lungs and skin. Although inhalation of smoke from open burning of dumpsites seem to be the major route of exposure to e-waste toxicants, drinking of contaminated water, ingestion of vegetables and fruits harvested from dumpsites, and dermal contacts are plausibly additional sources of e-waste related toxicants exposure. When agricultural lands (crops, cereals including rice, other vegetable foods) and animal-rearing activities (farming, fishing and aquaculture) are developed along or downstream of rivers, these should be prioritized in environmental remediation campaigns. Waterways used for domestic uses (drinking, cooking and washing) and irrigation should be prioritized as well. Zoonotic diseases include those which impact human health and result from exposure to toxicants through foods of animal origin.[1] Toxicant-related zoonoses are linked with the environment-feed-food chain.[37] The increasing urbanization of many cities in sub-Saharan Africa has made land for urban agriculture economically prohibitive with attendant socioeconomic pressures for those who engage in the practice for their livelihood.[14] As a result, many urban farmers are compelled to live and work in available and affordable but dangerous locations, without the necessary resources to protect themselves and/or guarantee the safety of their crops. The ultimate desire to feed themselves overrides safety and wellness considerations. Most farmers have dammed highly contaminated drains to harvest water to irrigate their farms, and the lands on which they farm are affected by e-waste recycling activities of significant public health relevance.[14,38]

E-waste pollutants are found at significant doses in human serum, blood, hair, placenta, breast milk, and umbilical cord blood, indicating that exposure to e-waste presents a risk for the present as well as for future generations. Most e-waste-related toxicants are persistent (slow excretion/metabolic rate) and therefore can bioaccumulate in living organisms (e.g. grazing animals and humans) as well as biomagnify in the food chain (e.g. fish). In addition, bioaccumulation results in the presence of multiple toxicants in the same organism, with potential mixture (additivity/potentiation) effects. E-waste does not constitute a contamination "event", but a background exposure that exceeds the (environmental, animal, human) detoxification rate, thus making the burden continuously re-established and amplified. The management of e-waste implies long-range initiatives, from the expected international regulation of the e-waste flow to the implementation of proper infrastructures and protocols for disposal and recycling and the remediation of environmental compartments on a large scale through innovative detoxification technologies.

Health effects

Chemicals in e-waste materials can accumulate in water, soil, and surrounding vegetation. Toxic and genotoxic levels can induce adverse ecological and human health effects.[16,39] Soil leachate and well water samples from the Alaba international and Computer village electronic markets in Lagos State, Nigeria showed both mutagenic and genotoxic properties in plant and animal models.[16,24,25,40-42] Exposure of *T. guineensis* juveniles to varying concentrations of e-waste leachate could be genotoxic to fish.[39] Hazardous heavy metals such as As, Cd, Hg, Pb from e-waste are known to cause cancer.[43] In their study "Perceived public health effects of occupational and residential exposure to electronic wastes in Lagos, Nigeria" the authors reported cases of cancer among e-waste workers who had spent at least 6 years or more in e-waste sites.[31] Similarly, Bandowe and Nkansah reported cases of cancer among those exposed to organic pollutants, as inhalation of e-waste fumes can cause lung cancer.[44,45] Decreased lung function arising from lung damage and lung cancer are also associated with PAHs, As, Cd, Cr(VI), Li, and Ni in e-waste.[46,47] The extent to which e-waste exposure has contributed to cancer remains largely unknown and should be further investigated.[48-50] In human lymphocytes, soil and plant samples from e-waste dumping and processing sites induced significant concentration-dependent increases in DNA damage compared with the negative control.[16] Exposure to dioxins, DL-PCBs, perfluoroalkyls and metals (e.g. Cd, Pb) are associated with increased incidence of metabolic syndrome, obesity, type 2 diabetes, hypertension, and cardiovascular diseases.[51-53] Exposure to PBDEs in dust has been associated with abnormal thyroid and reproductive functions in both children and adults in Nigeria.[54] In addition, heavy metals are endocrine disruptors. Aluminum, As, boron (B), Cd, Co, Cr, Hg, Li, Pb, Sb have been reported to exert negative effects on reproductive parameters of humans and animals. E-waste exposure contributes to rising infertility in sub-Saharan Africa.[55] Toxic levels of Pb exposure have shown adverse effects on male reproductive capacity; this is well known despite controversies on the effect of low to moderate doses or route and duration of exposure.[56,57] Occupational exposure to Cr(VI) caused significantly higher serum follicle-stimulating hormone concentration and lower sperm count and motility, lower seminal plasma Zn levels, lactate dehydrogenase, and lactate dehydrogenase-C4 according to Marouani *et al*.[58] Mean BLLs of women of childbearing age ranged from 0.83 to 99 µg/dl in sub-Saharan African, with an overall weighted mean of 24.73 µg/dl and 26.24 µg/dl for pregnant women alone.[59] Elevated BLLs were associated with the incidence of preeclampsia, hypertension, and malaria.[59] Spontaneous abortion has been reported among e-waste workers in Alaba international and Computer village electronic markets in Lagos.[31]

Developing countries, particularly in Africa, lack data on PCBs in abiotic and biotic matrices. Blood POPs levels of South African pregnant women showed low PCBs levels.[60] The serum levels and temporal trends of POPs in adults from Guinea-Bissau showed a significant decrease in total PCB levels (CB-138, CB-153, CB-170, CB-180, and CB-187) measured between 1990 and 2007.[61] Total PCBs concentration (sum of 62 congeners) in human milk samples from different parts of Ghana varied between 15 and 160 ng/g lw, with a mean of 62 ng/g lw.[34] The PCBs concentrations averaged 82 ng/g lw in Accra, 65 ng/g lw in Kumasi, and 30 ng/g lw in Tamale. Prenatal PCBs and PBDEs exposure are associated with thyroid hormone disruption which affects the initiation and modulation of gene expressions for brain development.[62,63]

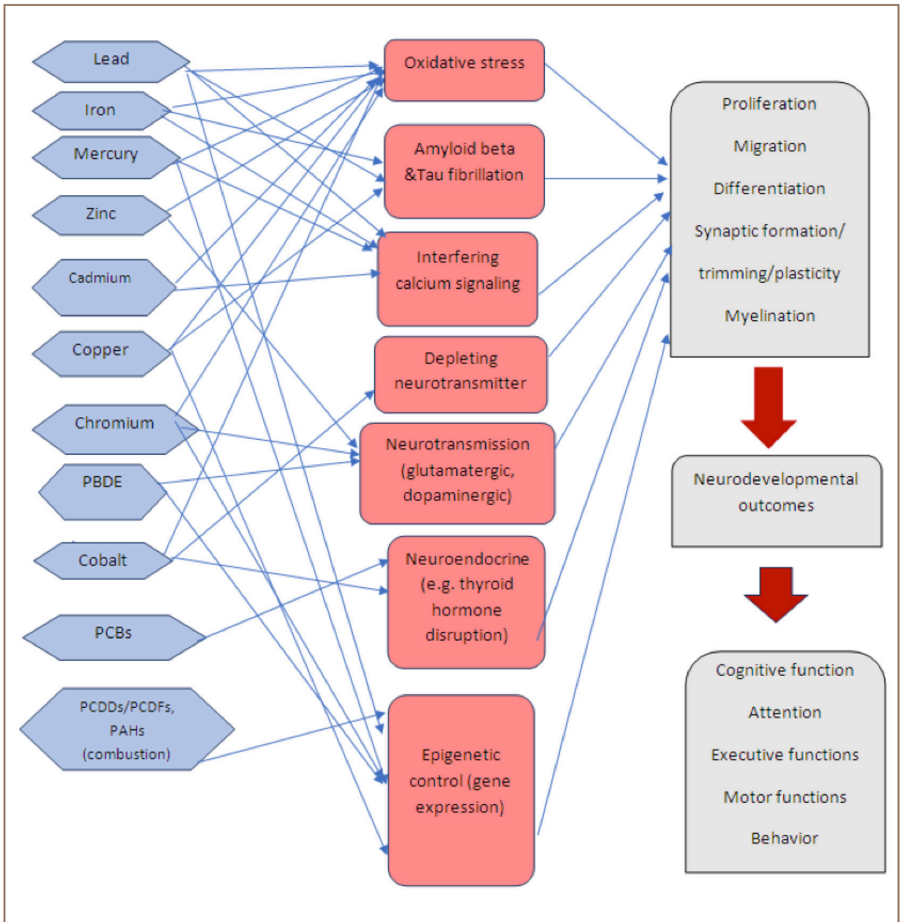

Figure 2 — E-waste neurotoxicants, their mechanisms and neurological effects during neurodevelopment

Among other health impacts (e.g. endocrine disruption, immunotoxicity), e-waste acts as a neurotoxicant in neurodevelopment and neurodegeneration. Along with endocrine disruption, neurotoxicity is considered the main e-waste-related health burden issue.[64] Heavy metals accumulate and substitute nutritional essential elements, for example calcium is substituted by Pb, Zn is substituted by Cd, and majority of trace elements are substituted by Al. Consequently, accumulated heavy metals destroy various and vital metabolic processes, and alter activity of hormones and essential enzyme's function along with creating antioxidant imbalance.[65] These mechanisms ultimately alter the synthesis of neurotransmitters and their use in the body thus altering central nervous system functions. Figure 2 presents e-waste neurotoxicants, their mechanisms and neurological effects during neurodevelopment. The neurotoxicological mechanisms of the effect of e-waste's mixture of toxicants are complicated and may be synergistic. Other mechanisms related to molecular biology and signal transduction may be involved in neurodegeneration. In a study of motor neuron disease in Nigeria, most patients were found to have lived in Warri, an area located in Nigeria's Niger Delta that is associated with petroleum activities. Some of these subjects worked at the National Petroleum Corporation.[66] Petroleum products have been reported as risk factors for the development of motor neuron disease and other neurodegenerative diseases.[67] Elevated soil metals levels have been cited as risk factors in neurodegenerative diseases.[68,69] In a multi-center case-control study of Nigerian patients and trace metals in patients with Parkinson's disease, Ogunrin *et al*. demonstrated elevated plasma levels of Cu, Fe, Zn, magnesium, and Mn in patients with Parkinson's disease living in the central, southwest and Niger Delta, Nigeria.[70] Notwithstanding that age is thought to be the single most consistent risk factor in Parkinson disease, environmental exposure to metals plays a role in the etiology of Parkinson disease, and increases the prevalence of Parkinson's disease with significant mortality. Finally, e-waste-related toxicants may have deleterious effects on immune and nutritional status, and pose an increased risk of chronic and infectious diseases, e.g. HIV, and harm therapeutic outcomes.[71]

Reported/diagnosed health effects of exposure to e-waste related organic and inorganic mixtures of toxicants (*Supplemental Material*) seem well in line with those expected based on toxicology.[12] Headache, cough and chest pain, stomach discomfort, miscarriage, abnormal thyroid and reproductive function, reduction of gonadal hormone and cancer are common complaints of the e-waste community, including vulnerable populations like pregnant women and children.

Conclusions

Dwindling economic fortunes, poverty and population explosion have led to a high level of unemployment in Nigeria and many sub-Saharan African countries. This has made e-waste handling, recycling and associated activities inevitable alternatives. The recycling of electronic waste, or e-waste, remains a major source of survival for the poor in urban areas in developing countries. Unfortunately, this economic activity presents severe risks to their health, as well as that of the general population and the environment. Most e-waste recycling sites in sub-Saharan Africa consist of a large number of support facilities such as housing and restaurants, street trading, food and beverage vendors, and therefore chemical exposure extends beyond e-waste workers. These communities, including women and children, comingle in these sites on a daily basis.

Until recently, there has been no available data on chemical exposure at e-waste recycling sites in sub-Saharan Africa, but this scenario is changing and the scientific community in Africa has begun to address the problem of e-waste. Human biomonitoring of metals and BFRs, as well as dioxins, PAHs, PCBs and furans in e-waste sites is recommended to validate the growing evidence of the negative environmental impacts and health concerns arising from uncontrolled informal e-waste recycling and disposal.

Acknowledgments

The authors acknowledge the efforts of the non-profit African organization Noodles (www.noodlesonlus.org) in boosting environmental health and food safety in Africa.

This study was funded as part of employment.

References

1. **Frazzoli C, Mantovani A.** Toxicants exposures as novel zoonoses: reflections on sustainable development, food safety and veterinary public health. Zoonoses Public Health [Internet]. 2010 Dec [cited 2019 May 8];57(7-8):e136-42. Available from: https://doi.org/10.1111/j.1863-2378.2009.01309.x Subscription required to view.
2. **Kiddee P, Naidu R, Wong MH.** Electronic waste management approaches: an overview. Waste Manag [Internet]. 2013 May [cited 2019 May 8];33(5):1237-50. Available from: https://doi.org/10.1016/j.wasman.2013.01.006 Subscription required to view.
3. **Robinson BH.** E-waste: an assessment of global production and environmental impacts. Sci Total Environ [Internet]. 2009 Dec 20 [cited 2019 May 8];408(2):183-91. Available from: https://doi.org/10.1016/j.scitotenv.2009.09.044 Subscription required to view.
4. **Williams E, Kahhat R, Allenby B, Kavazanjian E, Kim J, Xu M.** Environmental, social, and economic implications of global reuse and recycling of personal computers. Environ Sci Technol. 2008 Sep 1;42(17):6446-54.
5. **Frazzoli C, Orisakwe OE, Dragone R, Mantovani A.** Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. Environ Impact Assess Rev [Internet]. 2010 Nov [cited 2019 May 8];30(6):388-99. Available from: https://doi.org/10.1016/j.eiar.2009.12.004 Subscription required to view.
6. **Terada C.** Recycling electronic wastes in Nigeria: putting environmental and human rights at risk. Northwest J Hum Rights [Internet]. 2012 Spring [cited 2019 May 8];10(3):154-72. Available from: https://scholarlycommons.law.northwestern.edu/njihr/vol10/iss3/2/
7. **Kyere VN, Greve K, Atiemo SM.** Spatial assessment of soil contamination by heavy metals from informal electronic waste recycling in Agbogbloshie, Ghana. Environ Health Toxicol [Internet]. 2016 Mar 17 [cited 2019 May 8];31:Article e2016006 [10 p.]. Available from: https://doi.org/10.5620/eht.e2016006
8. **Hosoda J, Ofosu-Anim J, Sabi EB, Akita LG, Onwona-Agyeman S, Yamashita R, Takada H.** Monitoring of organic micropollutants in Ghana by combination of pellet watch with sediment analysis: e-waste as a source of PCBs. Mar Pollut Bull [Internet]. 2014 Sep 15 [cited 2019 May 8];86(1-2):575-81. Available from: https://doi.org/10.1016/j.marpolbul.2014.06.008 Subscription required to view.
9. **Bergman A, Heindel JJ, Jobling S, Kidd KA, Zoeller RT, editors.** State of the science of endocrine disrupting chemicals - 2012 [Internet]. Geneva, Switzerland: World Health Organization; 2013 [cited 2019 May 9]. 289 p. Available from: https://www.who.int/ceh/publications/endocrine/en/
10. **Sindiku O, Babayemi J, Osibanjo O, Schlummer M, Schluep M, Watson A, Weber R.** Polybrominated diphenyl ethers listed as Stockholm Convention POPs, other brominated flame retardants and heavy metals in e-waste polymers in Nigeria. Environ Sci Pollut Res Int [Internet]. 2015 Oct [cited 2019 May 9];22(19):14489-501. Available from: https://doi.org/10.1007/s11356-014-3266-0 Subscription required

to view.

11. **Weber R, Aliyeva G, Vijgen J. The need for an integrated approach to the global challenge of POPs management.** Environ Sci Pollut Res Int [Internet]. 2013 Apr [cited 2019 May 9];20(4):1901-6. Available from: https://doi.org/10.1007/s11356-012-1247-8 Subscription required to view.

12. **Frazzoli C, Mantovani A, Orisakwe OE. Electronic waste and human health.** In: Nriagu JO, editor. Encyclopedia of environmental health [Internet]. Amsterdam, Netherlands: Elsevier; 2011 [cited 2019 May 9]. p. 269-81. Available from: https://doi.org/10.1016/B978-0-444-52272-6.00572-9 Subscription required to view.

13. **Brigden K, Labunska I, Santillo D, Johnston P. Chemical contamination at e-waste recycling and disposal sites in Accra and Korforidua, Ghana** [Internet]. Amsterdam, Netherlands: Greenpeace Research Laboratories; 2008 Aug [cited 2019 May 9]. 24 p. Available from: http://www.greenpeace.to/publications/chemical-contamination-at-e-wa.pdf

14. **Oteng-Ababio M, Chama MA, Amankwaa EF. Qualitative analysis of the presence of PBDE in ashes, soils and vegetables from Agbogbloshie e-waste recycling site.** E3 J Environ Res Manag [Internet]. 2014 Apr [cited 2019 May 9];5(4):71-80. Available from: http://www.e3journals.org/cms/articles/1397776246_Martin%20et%20al.pdf

15. **Ikechukwu OA, Obinnaya CL. Haematological profile of the African lungfish, Protopterus annectens (Owen) of Anambra River, Nigeria.** J Am Sci [Internet]. 2010 [cited 2019 May 9];6(2): 123-30. Available from: http://www.jofamericanscience.org/journals/am-sci/am0602/21_1201_Haematological_am0602.pdf

16. Alabi OA, Bakare AA, Xu X, Li B, Zhang Y, Huo X. Comparative evaluation of environmental contamination and DNA damage induced by electronic-waste in Nigeria and China. Sci Total Environ [Internet]. 2012 Apr 15 [cited 2019 May 9];423:62-72. Available from: https://doi.org/10.1016/j.scitotenv.2012.01.056 Subscription required to view.

17. Caravanos J, Clark E, Fuller R, Lambertson C. Assessing worker and environmental chemical exposure risks at an e-waste recycling and disposal site in Accra, Ghana. J Health Pollut [Internet]. 2011 Feb [cited 2019 May 9];1(1):16-25. Available from: https://doi.org/10.5696/jhp.v1i1.22

18. Environmental Protection Agency (US). Lead; identification of dangerous levels of lead. Final rule. Fed Regist [Internet]. 2001 Jan 5 [cited 2019 May 9];66(4):1205-40. Available from: https://www.federalregister.gov/documents/2001/01/05/01-84/lead-identification-of-dangerous-levels-of-lead

19. Fujimori T, Itai T, Goto A, Asante KA, Otsuka M, Takahashi S, Tanabe S. Interplay of metals and bromine with dioxin-related compounds concentrated **in e-waste open burning soil from Agbogbloshie in Accra, Ghana.** Environ Pollut [Internet]. 2016 Feb [cited 2019 May 9];209:155-63. Available from: https://doi.org/10.1016/j.envpol.2015.11.031 Subscription required to view.

20. **Leung AO, Zheng J, Yu CK, Liu WK, Wong CK, Cai Z, Wong MH. Polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins and dibenzofurans in surface dust at an e-waste processing site in Southeast China.** Environ Sci Technol. 2011 Jul 1;45(13):5775-82.

21. **Tue NM, Takahashi S, Suzuki G, Isobe T, Viet PH, Kobara Y, Seike N, Zhang G, Sudaryanto A, Tanabe S. Contamination of indoor dust and air by polychlorinated biphenyls and brominated flame retardants and relevance of non-dietary exposure in Vietnamese informal e-waste recycling sites.** Environ Int [Internet]. 2013 Jan [cited 2019 May 10];51:160-7. Available from: https://doi.org/10.1016/j.envint.2012.11.006

22. **Quinn LP, Roos C, Pieters R, Loken K, Polder A, Skaare JU, Bouwman H. Levels of PCBs in wild bird eggs: considering toxicity through enzyme induction potential and molecular structure.** Chemosphere [Internet]. 2013 Jan [cited 2019 May 10];90(3):1109-16. Available from: https://doi.org/10.1016/j.chemosphere.2012.09.016 Subscription required to view.

23. **Long ER, Macdonald DD, Smith SL, Calder FD. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments.** Environ Manag [Internet]. 1995 Jan [cited 2019 May 10];19(1):81-97. Available from: https://doi.org/10.1007/BF02472006 Subscription required to view.

24. **Bakare AA, Alabi OA, Gbadebo AM, Ogunsuyi OI, Alimba CG. In vivo cytogenotoxicity and oxidative stress induced by electronic waste leachate and contaminated well water.** Chall [Internet]. 2013 Jul [cited 2019 May 10];4(2):169-87. Available from: https://doi.org/10.3390/challe4020169

25. **Alabi OA, Bakare AA. Cytogenotoxic effects and reproductive abnormalities induced by e-waste contaminated underground water in mice.** Cytol [Internet]. 2014 [cited 2019 May 10];79(3):331-40. Available from: https://doi.org/10.1508/cytologia.79.331

26. **Amankwaa EF, Adovor Tsikudo KA, Bowman JA. Away' is a place: the impact of electronic waste recycling on blood lead levels in Ghana.** Sci Total Environ [Internet]. 2017 Dec 1 [cited 2019 May 10];601-602:1566-74. Available from: https://doi.org/10.1016/j.scitotenv.2017.05.283 Subscription required to view.

27. **Akortia E, Olukunle OI, Daso AP, Okonkwo JO. Soil concentrations of polybrominated diphenyl ethers and trace metals from an electronic waste dump site in the Greater Accra Region, Ghana: implications for human exposure.** Ecotoxicol Environ Saf [Internet]. 2017 Mar [cited 2019 May 10];137:247-55. Available from: https://doi.org/10.1016/j.ecoenv.2016.12.008 Subscription required to view.

28. **Srigboh RK, Basu N, Stephens J, Asampong E, Perkins M, Neitzel RL, Fobil J. Multiple elemental exposures amongst workers at the Agbogbloshie electronic waste (e-waste) site in Ghana.** Chemosphere [Internet]. 2016 Dec [cited 2019 May 10];164:68-74. Available from: https://doi.org/10.1016/j.chemosphere.2016.08.089 Subscription required to view.

29. **Igharo OG, Anetor JI, Osibanjo O, Osadolor HB, Odazie EC, Uche ZC. Endocrine disrupting metals lead to alteration in the gonadal hormone levels in Nigerian e-waste workers.** Universa Medicina [Internet]. 2018 Jan-Apr [cited 2019 May 10];37(1):65-74. Available from: http://dx.doi.org/10.18051/UnivMed.2018.v37.65-74

30. **Asampong E, Dwuma-Badu K, Stephens J, Srigboh R, Neitzel R, Basu N, Fobil JN. Health seeking behaviours among electronic waste workers in Ghana.** BMC Public Health [Internet]. 2015 [cited 2019 May 10];15:Article 1065 [9 p.]. Available from: https://doi.org/10.1186/s12889-015-2376-z

31. **Alabi OA, Bakare AA. Perceived public health effects of occupational and residential exposure to electronic wastes in Lagos, Nigeria.** Zool. 2015 Dec;13:62-71.

32. **Otsuka M, Itai T, Asante KA, Muto M, Tanabe S. Trace element contamination around the e-waste recycling site at Agbogbloshie, Accra City, Ghana.** In: Kawaguchi M, Misaki K, Sato H, Yokokawa T, Itai T, Nguyen TM, Ono J, Tanabe S. Interdisciplinary studies on environmental chemistry. Vol. 6, Advanced environmental studies by young scientist [Internet]. Tokyo, Japan: Terrapub; 2012 [cited 2019 May 10]. p. 161-7. Available from: https://www.terrapub.co.jp/onlineproceedings/ec/06/pdf/PR620.pdf

33. **Darnerud PO, Aune M, Larsson L, Lignell S, Mutshatshi T, Okonkwo J, Botha B, Agyei N.**

Levels of brominated flame retardants and other pesistent organic pollutants in breast milk samples from Limpopo province, South Africa. Sci Total Environ [Internet]. 2011 Sep 1 [cited 2019 May 10];409(19):4048-53. Available from: https://doi.org/10.1016/j.scitotenv.2011.05.054 Subscription required to view.

34. **Asante KA, Adu-Kumi S, Nakahiro K, Takahashi S, Isobe T, Sudaryanto A, Devanathan G, Clarke E, Ansa-Asare OD, Dapaah-Siakwan S, Tanabe S. Human exposure to PCBs, PBDEs and HBCDs in Ghana: temporal variation, sources of exposure and estimation of daily intakes by infants.** Environ Int [Internet]. 2011 Jul [cited 2019 May 9];37(5):921-8. Available from: https://doi.org/10.1016/j.envint.2011.03.011 Subscription required to view.

35. **Feldt T, Fobil JN, Wittsiepe J, Wilhelm M, Till H, Zoufaly A, Burchard G, Goen T. High levels of PAH-metabolites in urine of e-waste recycling workers from Agbogbloshie, Ghana.** Sci Total Environ [Internet]. 2014 Jan 1 [cited 2019 May 10];466-467:369-76. Available from: https://doi.org/10.1016/j.scitotenv.2013.06.097 Subscription required to view.

36. **Liu H, Zhou Q, Wang Y, Zhang Q, Cai Z, Jiang G. E-waste recycling induced polybrominated diphenyl ethers, polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins and dibenzo-furans pollution in the ambient environment.** Environ Int [Internet]. 2008 Jan [cited 2019 May 10];34(1):67-72. Available from: https://doi.org/10.1016/j.envint.2007.07.008 Subscription required to view.

37. **Frazzoli C, Asongalem EA, Orisakwe OE, editors. Cameroon-Nigeria-Italy scientific cooperation: veterinary public health and sustainable food safety to promote "one health/one prevention".** Rome, Italy: Istituto Superiore di Sanità; 2012. 198 p.

38. **Pinto VN.** E-waste hazard: the impending **challenge.** Indian J Occup Environ Med [Internet]. 2008 Aug [cited 2019 May 10];12(2):65-70. Available from: http://www.ijoem.com/text.asp?2008/12/2/65/43263

39. **Igbo JK, Chukwu LO, Oyewo EO, Zelikoff JT, Jason B. Micronucleus assay and heavy metals characterization of e-waste dumpsites in Lagos and Osun States, Southwest Nigeria.** J Appl Sci Environ Manag. 2018;22(3):329-37.

40. **Alabi OA, Bakare AA. Genotoxicity and mutagenicity of electronic waste leachates using animal bioassays.** Toxicol Environ Chem [Internet]. 2011 [cited 2019 May 10];93(5):1073-88. Available from: https://doi.org/10.1080/02772248.2011.561949 Subscription required to view.

41. **Bakare AA, Adeyemi AO, Adeyemi A, Alabi OA, Osibanjo O. Cytogenotoxic effects of electronic waste leachate in Allium cepa. Caryologia** [Internet]. 2012 [cited 2019 May 10];65(2): 94-100. Available from: https://doi.org/10.1080/00087114.2012.709786

42. **Alabi OA, Bakare AA, Filippin-Monteiro FB, Sierra JA, Creczynski-Pasa TB. Electronic waste leachate-mediated DNA fragmentation and cell death by apoptosis in mouse fibroblast (NIH/3T3) cell line.** Ecotoxicol Environ Saf [Internet]. 2013 Aug [cited 2019 May 10];94:87-93. Available from: https://doi.org/10.1016/j.ecoenv.2013.05.004 Subscription required to view.

43. **Singh M, Thind PS, John S. Health risk assessment of the workers exposed to the heavy metals in e-waste recycling sites of Chandigarh and Ludhiana, Punjab, India.** Chemosphere [Internet]. 2018 Jul [cited 2019 May 10];203:426-33. Available from: https://doi.org/10.1016/j.chemosphere.2018.03.138 Subscription required to view.

44. **Bandowe BA, Nkansah MA. Occurrence, distribution and health risk from polycyclic aromatic compounds (PAHs, oxygenated-PAHs and azaarenes) in street dust from a major West African Metropolis.** Sci Total Environ [Internet]. 2016 May 15 [cited 2019 May 10];553:439-49. Available from: https://doi.org/10.1016/j.scitotenv.2016.02.142 Subscription required to view.

45. **Wang J, Chen S, Tian M, Zheng X, Gonzales L, Ohura T, Mai B, Simonich SL. Inhalation cancer risk associated with exposure to complex polycyclic aromatic hydrocarbon mixtures in an electronic waste and urban area in South China.** Environ Sci Technol. 2012 Sep 4;46(17):9745-52.

46. **Abakay A, Gokalp O, Abakay O, Evliyaoglu O, Sezgi C, Palanci Y, Ekici F, Karakus A, Tanrikulu AC, Ayhan M. Relationships between respiratory function disorders and serum copper levels in copper mineworkers.** Biol Trace Elem Res [Internet]. 2012 Feb [cited 2019 May 10];145(2):151-7. Available from: https://doi.org/10.1007/s12011-011-9184-9 Subscription required to view.

47. **Martin AK, Mack DG, Falta MT, Mroz MM, Newman LS, Maier LA, Fontenot AP. Beryllium-specific CD4+ T cells in blood as a biomarker of disease progression.** J Allergy Clin Immunol [Internet]. 2011 Nov [cited 2019 May 10];128(5):1100-6. e1-5. Available from: https://doi.org/10.1016/j.jaci.2011.08.022

48. **Fasinu P, Orisakwe OE. Heavy metal pollution in sub-Saharan Africa and possible implications in cancer epidemiology.** Asian Pac J Cancer Prev. 2013 Jun;14(6):3393-402.

49. **Orisakwe OE, Frazzoli C. Electronic revolution and electronic wasteland: the west / waste Africa experience.** J Nat Environ Sci. 2010;1:43-7.

50. **Davis JM, Garb Y. A strong spatial association between e-waste burn sites and childhood lymphoma in the West Bank, Palestine.** Int J Cancer [Internet]. 2019 Feb 1 [cited 2019 May 10];144(3):470-75. Available from: https://doi.org/10.1002/ijc.31902 Subscription required to view.

51. **Pasanen K, Pukkala E, Turunen AW, Patama T, Jussila I, Makkonen S, Salonen RO, Verkasalo PK. Mortality among population with exposure to industrial air pollution containing nickel and other toxic metals.** J Occup Environ Med. 2012 May;54(5):583-91.

52. **Halldorsson TI, Rytter D, Haug LS, Bech BH, Danielsen I, Becher G, Henriksen TB, Olsen SF. Prenatal exposure to perfluorooctanoate and risk of overweight at 20 years of age: a prospective cohort study.** Environ Health Perspect [Internet]. 2012 May [cited 2019 May 10];120(5):668-73. Available from: https://doi.org/10.1289/ehp.1104034

53. **Everett CJ, Frithsen I, Player M. Relationship of polychlorinated biphenyls with type 2 diabetes and hypertension.** J Environ Monit. 2011 Feb;13(2):241-51.

54. **Olukunle OI, Okonkwo OJ, Sha'ato R, Wase GA. Levels of polybrominated diphenyl ethers in indoor dust and human exposure estimates from Makurdi, Nigeria.** Ecotoxicol Environ Saf [Internet]. 2015 Oct [cited 2019 May 9];120:394-9. Available from: https://doi.org/10.1016/j.ecoenv.2015.06.023 Subscription required to view.

55. **Amadi CN, Igweze ZN, Orisakwe OE. Heavy metals in miscarriages and stillbirths in developing nations.** Middle East Fertil Soc J [Internet]. 2017 Jun [cited 2019 May 10];22(2):91-100. Available from: https://doi.org/10.1016/j.mefs.2017.03.003

56. **Adaramodu AA, Osuntogun AO, Ehi-Eromosele CO. Heavy metal concentration of surface dust present in e-waste components: the Westminister Electronic Market, Lagos case study.** Res Environ. 2012;2(2):9-13.

57. **Flora SJ, Pachauri V, Saxena G. Arsenic, cadmium and lead.** In: Gupta RC, editor. Reproductive and developmental toxicology. 1st ed. Cambridge, MA: Academic Press; 2011. p. 415-38.

58. **Marouani N, Tebourbi O, Mahjoub S, Yacoubi MT, Sakly M, Benkhalifa M, Rhouma KB. Effects of hexavalent chromium on reproductive functions of**

male adult rats. Reprod Biol [Internet]. 2012 Jul [cited 2019 May 10];12(2):119-33. Available from: https://doi.org/10.1016/S1642-431X(12)60081-3 Subscription required to view.

59. **Bede-Ojimadu O, Amadi CN, Orisakwe OE. Blood lead levels in women of child-bearing age in Sub-Saharan Africa: a systematic review.** Front Public Health [Internet]. 2018 Dec [cited 2019 May 10];6:367. Available from: https://doi.org/10.3389/fpubh.2018.00367

60. **Rollin HB, Sandanger TM, Hansen L, Channa K, Odland JO. Concentration of selected persistent organic pollutants in blood from delivering women in South Africa.** Sci Total Environ [Internet]. 2009 Dec 15 [cited 2019 May 10];408(1):146-52. Available from: https://doi.org/10.1016/j.scitotenv.2009.08.049 Subscription required to view.

61. **Linderholm L, Biague A, Mansson F, Norrgren H, Bergman A, Jakobsson K. Human exposure to persistent organic pollutants in West Africa--a temporal trend study from Guinea-Bissau.** Environ Int [Internet]. 2010 Oct [cited 2019 May 10];36(7):675-82. Available from: https://doi.org/10.1016/j.envint.2010.04.020 Subscription required to view.

62. **Liu L, Zhang B, Lin K, Zhang Y, Xu X, Huo X. Thyroid disruption and reduced mental development in children from an informal e-waste recycling area: a mediation analysis.** Chemosphere [Internet]. 2018 Feb [cited 2019 May 10];193:498-505. Available from: https://doi.org/10.1016/j.chemosphere.2017.11.059 Subscription required to view.

63. **Zheng J, He CT, Chen SJ, Yan X, Guo MN, Wang MH, Yu YJ, Yang ZY, Mai BX. Disruption of thyroid hormone (TH) levels and TH-regulated gene expression by polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and hydroxylated PCBs in e-waste recycling workers.** Environ Int [Internet]. 2017 May [cited 2019 May 10];102:138-144. Available from: https://doi.org/10.1016/j.envint.2017.02.009 Subscription required to view.

64. **Liu J, Xu X, Wu K, Piao Z, Huang J, Guo Y, Li W, Zhang Y, Chen A, Huo X. Association between lead exposure from electronic waste recycling and child temperament alterations.** Neurotoxicology [Internet]. 2011 Aug [cited 2019 May 10];32(4):458-64. Available from: https://doi.org/10.1016/j.neuro.2011.03.012 Subscription required to view.

65. **Mukke VK, Chinte DN. Impact of heavy metal induced alterations in Lipase activity of fresh water crab, Barytelphusa guerini.** J Chem Pharm Res. 2012 Jan;4(5):2763-6.

66. **Imam I, Ogunniyi A. What is happening to motor neuron disease in Nigeria?** Ann Afr Med. 2004;3(1):1-3.

67. **Zahran S, Laidlaw MA, Rowe DB, Ball AS, Mielke HW. Motor neuron disease mortality and lifetime petrol lead exposure: evidence from national age-specific and state-level age-standardized death rates in Australia.** Environ Res [Internet]. 2017 Feb [cited 2019 May 10];153:181-90. Available from: https://doi.org/10.1016/j.envres.2016.11.023 Subscription required to view.

68. **Shen XL, Yu JH, Zhang DF, Xie JX, Jiang H. Positive relationship between mortality from Alzheimer's disease and soil metal concentration in mainland China.** J Alzheimers Dis. 2014 Sep;42(3):893-900.

69. **Komatsu F, Kagawa Y, Kawabata T, Kaneko Y, Chimedregzen U, Purvee B, Otgon J.** A high **accumulation of hair minerals in Mongolian people: 2nd report; influence of manganese, iron, lead, cadmium and aluminum to oxidative stress, Parkinsonism and arthritis.** Curr Aging Sci. 2011 Feb;4(1):42-56.

70. **Ogunrin AO, Komolafe MA, Sanya EO, Osubor C, Ajose OA, Akande AA, Mosaku SK.** Trace metals **in patients with Parkinson's disease: a multi-center case-control study of Nigerian patients.** J Neurol Epidemiol [Internet]. 2013 [cited 2019 May 10];1:31-8. Available from: http://dx.doi.org/10.12974/2309-6179.2013.01.01.4

71. **Frazzoli C, Mazzanti F, Achu MB, Pouokam GB, Fokou E.** Elements of kitchen toxicology to **exploit the value of traditional (African) recipes: The case of Egusi Okra meal in the diet of HIV+/AIDS subjects.** Toxicol Rep [Internet]. 2017 [cited 2019 May 10];4:474-83. Available from: https://doi.org/10.1016/j.toxrep.2017.06.008